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MANEUVER OPERATIONS DURING JUNO'S APPROACH, ORBIT INSERTION, AND EARLY ORBIT PHASE

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The Juno spacecraft was launched on August 5, 2011 for a 1795-day journey to Jupiter, and arrived on July 5, 2016 with the successful Jupiter Orbit Insertion (JOI) maneuver. This paper will discuss the maneuver operations that took place starting from the Jupiter approach phase (specifically TCM11 on February 3, 2016) through JOI, and the first year of Juno orbital operations through OTM07.

INTRODUCTION

Juno is a solar-powered spin-stabilized spacecraft launched on August 5, 2011 that successfully entered into polar orbit at Jupiter on July 5, 2016. As one of NASA's New Frontiers programs, its mission is to study deep beneath the clouds of Jupiter and get a better understanding of its interior, magnetosphere, gravity, atmospheric structure and interactions.[1] Equipped with a suite of nine science instruments, the Juno mission hopes to answer fundamental questions surrounding the formation and evolution of Jupiter and, in turn, yield insight into the origins of the solar system and Earth itself. To reach Jupiter, Juno performed eight maneuvers and an Earth gravity assist on October 9, 2013. After a quiescent trip to Jupiter following the Earth flyby, spacecraft activity increased significantly during the Jupiter approach phase that began approximately five months prior to arrival.

This paper will discuss maneuver operation activities between February 2016 and July 2017 – an exciting time for the Juno maneuver team that spanned from Jupiter approach, five months prior to arrival, through the first year of Jupiter orbital operations. This time period included many important events. First, the mission's final Trajectory Correction Maneuver (TCM) was implemented to deliver the spacecraft to the desired target prior to performing the Jupiter Orbit Insertion (JOI) burn. The interplanetary phase of the mission came to an end with the successful implementation of the JOI burn 1795 days after launch. Following JOI, Juno entered the first of two 53.5-day capture orbits. These first two orbits allowed for a post-JOI perijove dedicated to collecting science data and provided an opportunity to assess spacecraft and instrument performance in the Jovian environment prior to entering the 14-day science orbits – where there would be less time to react to potential anomalies. From a navigation standpoint, the capture orbits allowed the team to reconstruct JOI, implement the JOI Clean-Up maneuver, design the first two Orbit Trim Maneuvers (OTMs), and develop the final design of the Period Reduction Maneuver (PRM) whose purpose is to deliver the spacecraft to a 14-day science orbit.

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In addition to capture orbit operations, this paper describes various changes to the navigation plan and maneuver strategy that were implemented following the Juno project's decision to cancel PRM due to the detection of an anomaly in the main-engine propulsion system. During the anomaly investigation, the Juno Navigation Team continued to perform operational activities while conducting various analyses and planning activities in support of a new baseline mission. Contingency maneuver design efforts following PRM cancellation, as well as nominal OTM design activities during the first year of science operations at Jupiter, are also discussed.

JUNO SPACECRAFT

The Juno mission stakes its claim as the farthest spacecraft from the Sun to operate completely on solar power. To achieve this technological feat, the spacecraft design is dominated by three large solar arrays as seen in Figure 1. The 8.7-meter-long wings give the spacecraft a spin diameter that

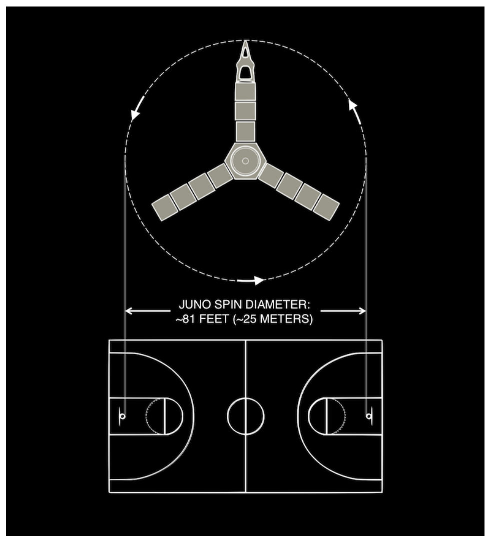


Figure 1. Juno Spacecraft Size Comparison

nearly spans the length of a basketball court. Juno is a spin-stabilized spacecraft that rotates about its body-fixed Z-axis, which is aligned with the High Gain Antenna (HGA) and points through the forward deck of the spacecraft bus. Juno has a suite of instruments that point outward from the spacecraft's spin axis and are designed to work in the harsh Jovian radiation environment. The solar wing with an attached magnetometer boom defines the X-axis and the Y-axis completes the right-handed spacecraft body-fixed frame. An illustration of the Juno spacecraft and its body-fixed frame definition appear in Figure 2.

The bi-propellant main-engine (ME) is located on the aft deck of the spacecraft and is oriented in the -Z direction, while the monopropellant reaction control system (RCS) thrusters are situated on four pylons along the Y-axis on the aft and forward decks to balance the RCS thrusters. Each pylon houses three thrusters – a single axial thruster and two lateral thrusters. The forward and aft RCS thruster pylon locations are shown in Figures 3(a) and 3(b), respectively. To avoid plume impingement on the instruments, the axial thrusters are canted 10 degrees away from the Z-axis, while the lateral thrusters are canted 5 degrees away from the X-axis and 12.5 degrees toward the Z-axis as depicted in Figure 3(c).

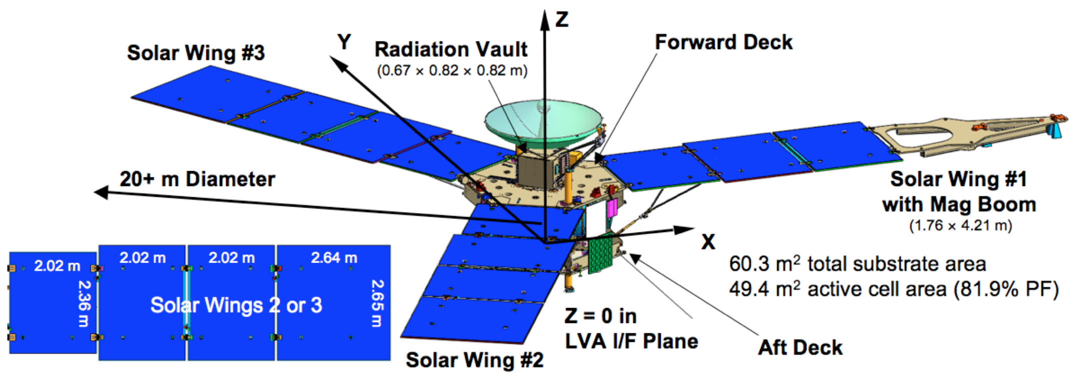
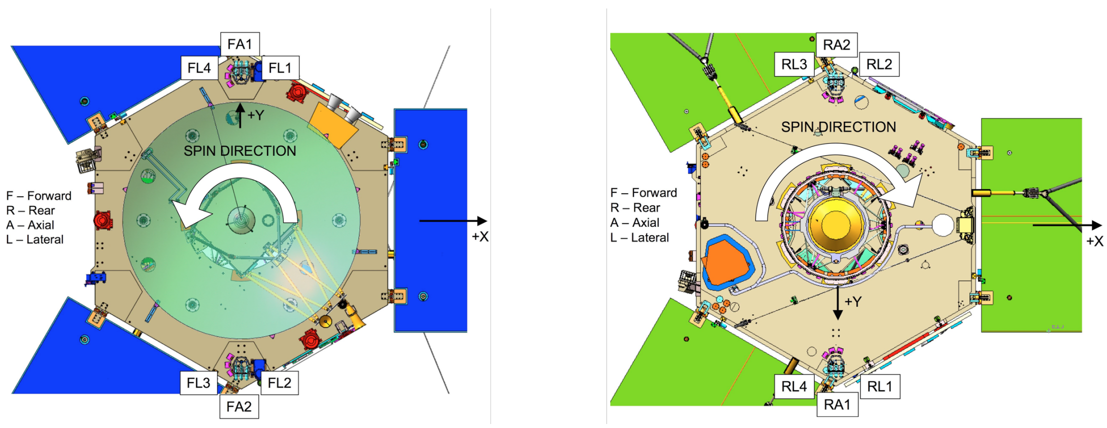
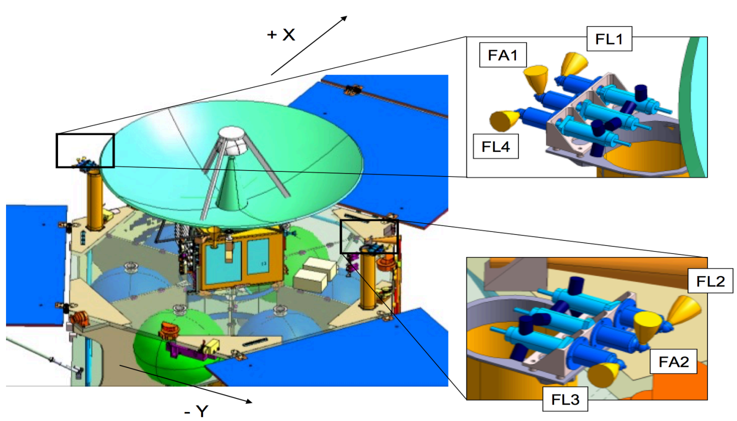


Figure 2. Juno Diagram with Body Fixed Axes



(a) Forward Deck

(b) Aft Deck



(c) Forward Deck RCS Thruster Configuration

Figure 3. Forward and Aft Views of the Juno Spacecraft

MANEUVER IMPLEMENTATION

The 662-Newton main-engine was designed to support Juno's four largest maneuvers: two Deep Space Maneuvers (DSM-1 and DSM2),[2] Jupiter Orbit Insertion, and the Period Reduction Maneuver (PRM). Main-engine maneuvers are conducted in a "turn-burn-turn" mode in which the entire spacecraft precesses to the desired attitude before executing the burn. For added stability, the spacecraft then spins up from one or two rotations per minute to five rotations per minute. Upon completion of the burn, the spacecraft then reduces the rotation rate to the nominal one or two rotations per minute – depending on the phase of the mission – and precesses to a power-positive attitude to recharge the batteries. RCS burns can also be implemented in turn-burn-turn mode, but to date, that setting has not been leveraged.

The 4.5-Newton RCS thrusters are used for spin control, attitude control, and for implementing all maneuvers that do not require the main-engine. For RCS maneuvers, the spacecraft performs the maneuvers in a "vector-mode." In the vector-mode strategy, the burn is performed at the nominal Earth-pointed spacecraft orientation and spin rate. To execute a maneuver in an arbitrary direction, the desired burn is decomposed into axial and lateral components. The axial thrusters are aligned with the Z-axis and, thus, can be pulsed nearly-continuously. The lateral thrusters, however, are pulsed as the spacecraft spins with a pulse width (or pulse duration) that depends on the spin rate of the spacecraft. The lateral burn arc is independent of the spin rate and is defined to be ± 30 degrees from the desired direction of the lateral burn. Since the center of mass is not located exactly at the center of the spacecraft, the commanded forward and aft lateral pulses are not the same length. Thus, as propellant is consumed during the mission, the ratio between forward and aft pulse durations is adjusted to compensate for the shifting center of mass. Lastly, since the lateral thrusters are canted, a component of the lateral burn is in the axial direction, as well. This "induced axial" component of the lateral burn is non-negligible and must be accounted for during the vector-mode maneuver design process.

REFERENCE TRAJECTORY AND MISSION PLAN

After launching on August 5, 2011, Juno required an Earth gravity assist on October 9, 2013 – providing an effective ΔV of 7300 m/s – en route to its rendezvous with Jupiter on July 5, 2016.[2] The Juno interplanetary trajectory appears in a tilted ecliptic view in Figure 4. Juno closely adhered to the planned trajectory during interplanetary cruise, however, the plan for orbital operations at Jupiter was modified substantially following Earth Flyby. In summary, the JOI magnitude was increased to capture into a 53.5-day orbit – instead of a 107-day orbit as originally planned. This change allowed for two capture orbits, instead of the one, while maintaining the PRM epoch on October 19, 2016 as planned. The capture orbits would provide an opportunity to check out the spacecraft and instruments in the harsh Jovian environment. Along with the change in JOI, PRM was modified to deliver the Juno spacecraft to a 14-day science orbit – instead of an 11-day science orbit as originally planned. These mission design changes are discussed in greater detail by Johannesen et al.[3] and Pavlak et al.[4] During the orbit phase, Juno does not have to strictly adhere to the reference trajectory for the whole orbit, however, the reference trajectory targets have to be met.

JUPITER APPROACH

The approach trajectory allotted four maneuver opportunities to ensure that Juno achieved the required Jupiter-relative orbital geometry prior to executing the critical JOI burn. The four ap-

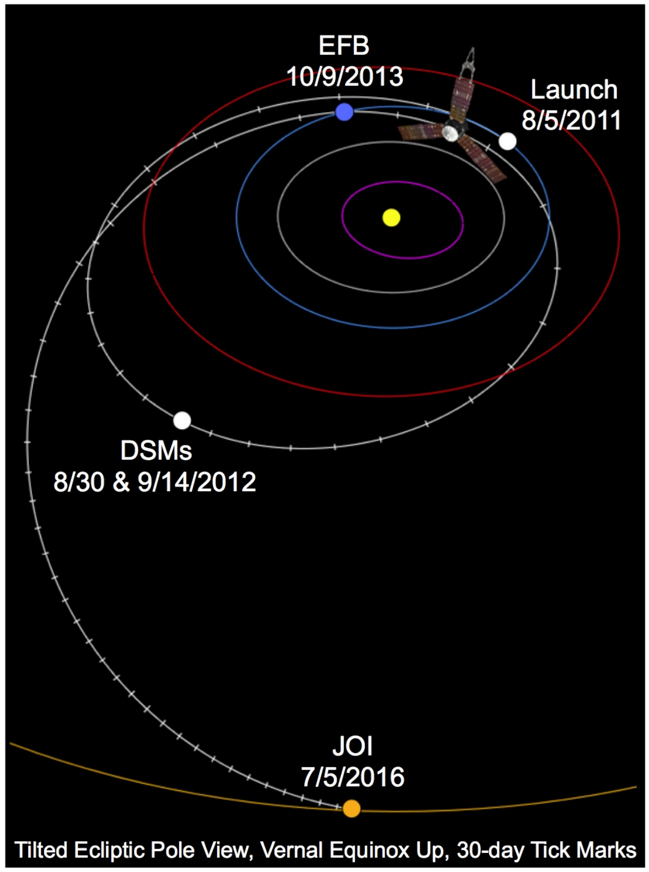


Figure 4. Juno Interplanetary Trajectory

proach maneuvers – TCM11, TCM12, TCM12a, and TCM13 – spanned the first half of 2016 and were scheduled on February 3, May 31, June 15, and June 25, respectively. TCM11 was the only deterministic approach maneuver and the others were in place for trajectory clean-up and/or pre-JOI contingency purposes. Ultimately, due to sufficiently small orbit determination and maneuver execution errors, only the first of these four maneuvers was implemented.

TCM11 was leveraged to adjust the final Jupiter encounter conditions and deliver Juno to the desired pre-JOI Cartesian state. The RCS maneuver had a magnitude of 0.307 m/s (0.279 m/s axial and 0.139 m/s lateral) and changed the B-plane predictions by 1193.48 km in $B \cdot R$ and 3185.43 km in $B \cdot T$. A description of the B-plane appears in in the Appendix A. TCM11 also changed the time of closest approach by 251.82 seconds. Figure 5 shows the B-plane change resulting from both the axial and lateral portions of the burn. TCM11 performed well, resulting in the eventual cancellation of TCM12, TCM12a and TCM13. For reference, the delivery accuracies and maneuver performance for all of the maneuvers presented in this paper can be found in Appendices B and C in Tables 2 and 3, respectively.

JOI

Once Juno arrived at Jupiter, the JOI maneuver was designed to reduce the Jupiter-relative velocity by 541.65 m/s, allowing the spacecraft to be captured into the aforementioned 53.5-day orbit.

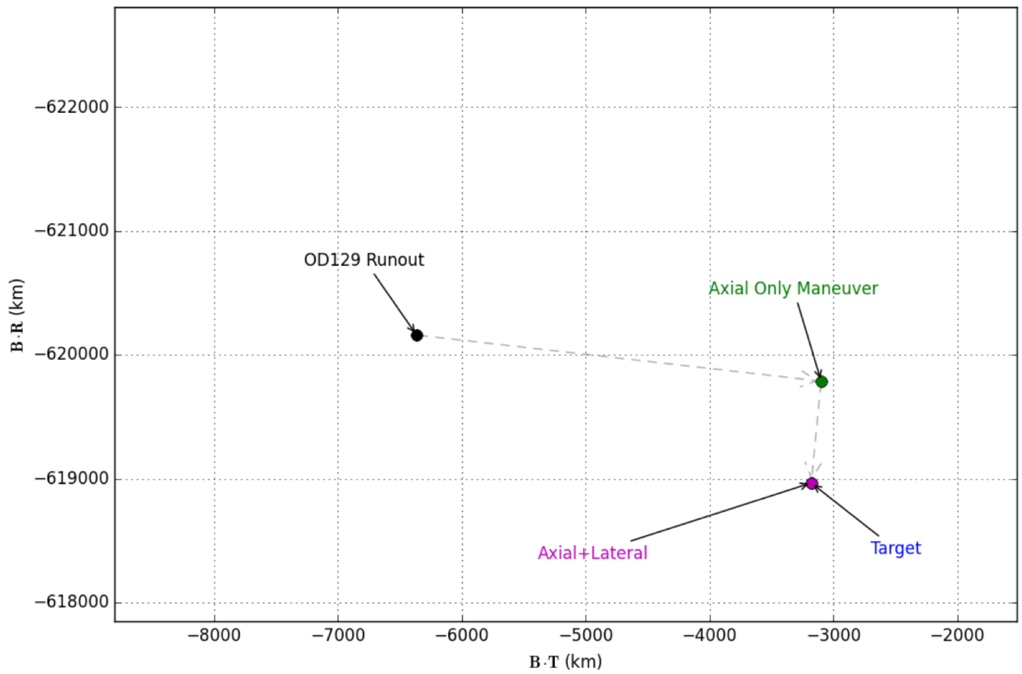


Figure 5. TCM11 B-plane Change Axial and Lateral Component

The JOI burn direction was inertially-fixed and approximately aligned with the spacecraft anti-velocity direction at perijove. JOI was designed as a main-engine burn centered around perijove, with a start time of July 5, 2017 at 02:30:00 UTC. JOI performed well within expectations, and after the full 2097.0-second burn was complete, Juno was safely captured into a 53.5-day orbit around Jupiter.[5] Since JOI was centered around perijove and implemented in a fixed inertial direction, the pre- and post-perijove components of any pointing error would cancel each other. Therefore, the JOI Clean-Up maneuver would primarily be tasked with cleaning up JOI maneuver magnitude errors.

CAPTURE ORBIT OPERATIONS

Following a successful JOI burn, up to three RCS maneuvers – JOI Clean-Up, OTM00, and OTM01 – were available to guide Juno through its first science perijove (PJ) pass and achieve the required orbit geometry prior to executing PRM at PJ02.

JOI Clean-Up

The JOI Clean-Up (JOI-CLN) maneuver was scheduled for July 13, 2016 17:58:51 UTC (18:00:00 ET) and was employed to counteract any execution errors imparted during JOI and to target Juno's first science perijove, PJ01. Unlike the TCMs during Juno's interplanetary phase, which primarily targeted B-Plane coordinates, RCS maneuvers during orbital operations are leveraged to target Jovian radius and longitude at a specific equator-crossing epoch. The Juno mission employs this targeting strategy to build an evenly-spaced grid of equator-crossing longitudes that will provide global coverage of Jupiter. The longitude grid associated with the current Juno reference trajectory appears in Figure 6.

JOI-CLN was a 4.918 m/s (1.155 m/s axial and 4.831 m/s lateral) maneuver that was implemented

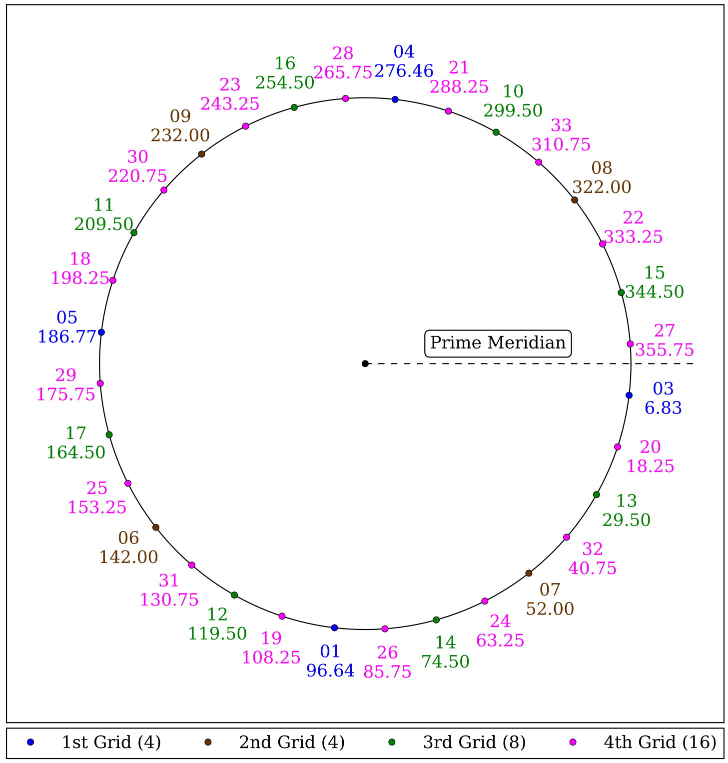


Figure 6. Juno Equator-Crossing Longitude Grid

on RCS thrusters. This maneuver lowered the equator-crossing radius by 237.3 km, changed the equator-crossing longitude 81.3 degrees, and adjusted the equator-crossing epoch by 8070 seconds. Given Juno's nearly-polar orbit, equator-crossing epoch and longitude are closely correlated, i.e., adjusting the equator-crossing epoch allows Jupiter more or less time to rotate beneath the spacecraft, altering the equator-crossing longitude. Note that any references to longitude in this paper should be assumed to be west longitude, unless otherwise stated. Juno has a science requirement to fly within ± 1 degree of the desired longitude. Figure 7 illustrates the green longitude target corridor in relation to the blue JOI-CLN delivery ellipse from a view looking down Jupiter equatorial plane. The delivery ellipse is too small to see at the scale shown in Figure 7. Other figures forthcoming will show a close-up view of the delivery ellipses. If no maneuver was implemented, the spacecraft would pierce the plane at the black "+" symbol. However, implementing JOI-CLN moves the descending equator-crossing to the blue "+" symbol, which is centered within the target corridor. After JOI-CLN was performed, preparations began for Juno's first orbit trim maneuver.

OTM00

OTM00 was a statistical maneuver that was scheduled near Juno's first apojove, APO0, on July 27, 2016 at 17:58:51 UTC. At the time, OTM00 was the only apojove maneuver planned during the entire Juno mission. Post-JOI-CLN orbit determination solutions indicated that Juno was already well within the longitude target corridor and OTM00 would have only been required to adjust radius and longitude by 6.7 km and 0.365 degrees, respectively. To achieve these small corrections, OTM00 would have been a 0.062 m/s maneuver (0.040 m/s axial and 0.049 m/s lateral). However, OTM00 was canceled given that Juno was already on target for its first science pass at PJ01.

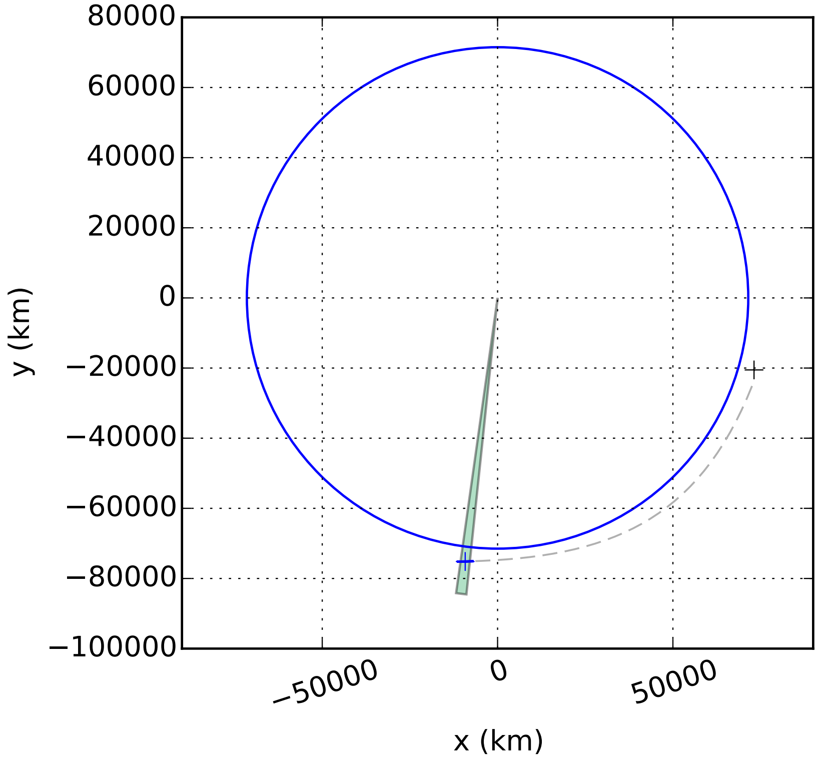


Figure 7. Juno Target Corridor with JOI-CLN Delivery Ellipse

OTM01

After a successful and exciting PJ01 equator-crossing on August 27, 2016, OTM01 was implemented 18 days after PJ01 on September 14, 2016 at 17:58:51 UTC (18:00:00 ET). The 18 days provided adequate time to design a maneuver if an issue arose at PJ01. The 0.604 m/s maneuver (-0.051 axial and 0.600 m/s lateral) lowered the radius by 15.6 km and changed the equator-crossing longitude by 5.4 degrees at PJ02 in order to achieve the desired orbit geometry prior to implementing the Period Reduction Maneuver.

PRM DELAY AND CHANGES TO THE MANEUVER OPERATIONS STRATEGY

The Juno spacecraft successfully traversed its two post-JOI capture orbits and was preparing to perform PRM at PJ02 when a series of onboard anomalies prompted significant short- and long-term changes to Juno's maneuver operations strategy.

PRM Delay

PRM was Juno's last planned main-engine maneuver and was designed to reduce the orbital period from 53 days to 14 days. In 14-day orbits, Juno was scheduled to complete its 37 orbits – including the 32 science orbits required to complete the equator-crossing longitude grid – on February 20, 2018. The PRM design was similar to JOI in that it was an inertially-fixed main-engine maneuver centered around perijove (PJ02). The maneuver was to start on October 19, 2016 at 18:00:00 UTC and was to deliver a ΔV of 395.17 m/s over the course of the 21-minute, 45.4-second burn.

Approximately one week prior to PRM execution, the project was proceeding through main-engine burn preparation procedures and a command was issued to pressurize the main-engine propulsion system. However, during the pressurization, spacecraft telemetry revealed that two helium check valves took several minutes to open, instead of opening instantaneously as expected. This anomalous behavior from the "sticky" check valves raised concerns about main-engine reliability and spacecraft safety during the PRM burn. Thus, several days before the burn was to execute, the Juno project decided to delay PRM indefinitely, pending an investigation into the anomalous check valve behavior.

OTM02

In the nominal mission plan, the PRM spacecraft attitude – nearly 90 degrees off the Earth-Juno line – and the fact that the burn was centered around perijove, meant that the PJ02 pass would not be counted as a conventional science pass and would not contribute to the equator-crossing longitude grid. However, following the decision to delay PRM, a new reference trajectory and associated longitude grid were developed that utilized PJ02 as a science pass. In the absence of PRM, an OTM02 was added to the mission (since there originally was not an OTM02 maneuver in the mission) and was performed on October 25, 2016 at 17:58:52 UTC, six days after PJ02. It was needed to achieve the updated PJ03 equator-crossing target, that is, a 75149.5-km radius and 277-degree west longitude. The OTM02 maneuver was designed to adjust the radius and longitude by approximately 690 km and 149 degrees, respectively, via a ΔV of 7.423 m/s (1.797 m/s axial and 7.292 m/s lateral) with an estimated duration of 5370 seconds.

Unfortunately, the Juno spacecraft entered safe mode hours before PJ02, the science instruments were automatically turned off, and no science data was recorded during the perijove pass. With this latest development, the reference trajectory and its corresponding equator-crossing longitude grid were redesigned again to account for the missed PJ02 science pass. In the updated reference trajectory, the time of the maneuver did not change, but the targets had to change. The new targets for PJ03 were 75772.7 km radius and 7 degrees west longitude. In this new paradigm, the redesigned OTM02 burn was only tasked with lowering the radius 67 km and adjusting the longitude by 59 degrees and, as a result, the maneuver ΔV magnitude was reduced to 2.618 m/s (0.585 m/s axial and 2.580 m/s lateral). Figure 8 shows the target corridor and 1-σ delivery arc for OTM02. A statistical burn to refine the PJ03 targeting, STM02, was scheduled for December 6, 2016 – five days prior to PJ03 – however, the OTM02 maneuver execution was sub-sigma, as shown in Table 2, and, thus, STM02 was canceled.

Changes to the Maneuver Operations Strategy

Following the decision to delay PRM, a wide-ranging trajectory trade study was launched that considered a variety of potential PRM epochs and science orbit periods.[4] However, following five months of investigation, the Juno project, with the approval of NASA Headquarters, ultimately decided to cancel PRM and maintain the spacecraft in 53-day orbits for the remainder of the mission.

The decision to remain in 53-day orbits prompted a reference trajectory redesign, and, consequently, a reexamination of Juno's maneuver operations strategy. The Juno navigation team performed a series of statistical maneuver analyses, which indicated that, given the increase in orbital period from 14 to 53 days, a single OTM per orbit would no longer be sufficient to achieve the required equator-crossing target delivery accuracy. Therefore, statistical trim maneuvers (STM) were added to the maneuver design cadence. If needed, STMs would take place every orbit and were

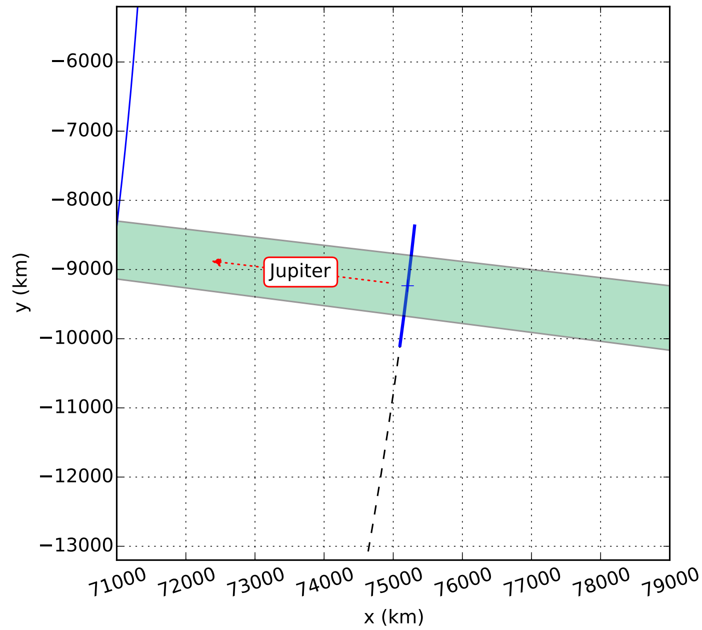


Figure 8. OTM02 Delivery Arc

scheduled 1-2 weeks prior to the subsequent perijove. Unlike the OTM maneuvers, which have backup opportunities – called BTMs – the STM maneuvers have no backup opportunity and provide one last opportunity to adjust the trajectory and correct any execution errors from the previous maneuver(s) prior to arriving at the next equator-crossing.

Additional navigation studies determined that, in the 53-day orbits, the perijove altitude increases much more quickly than in 14-day orbits. Therefore, it is necessary to control perijove altitude via frequent apojove maneuvers to maintain the requirement, 3500 km $\leq$ perijove altitude $\leq$ 8000 km. In the updated maneuver operations strategy, deterministic apojove maneuvers (APO) were added, when needed, with an accompanying backup apojove maneuvers (BPO) included seven days later. These changes meant that some orbits would now have up to five maneuver opportunities: OTM, BTM, APO, BPO, and STM. The five nominal maneuver locations appear in Figure 9. Nominally, OTMs and BTMs are scheduled 7.5 hours and 7 days after perijove, respectively. To allow adequate time between the BPO and subsequent STM, APO burns are, generally, implemented 7 days prior to apojove with the BPO opportunity positioned near apojove, itself. STMs are notionally scheduled two weeks prior to the subsequent perijove. Note that these event-relative maneuver times are only notional and, in reality, must be updated to accommodate external constraints such as solar conjunction and DSN tracking schedules.

Maneuver Naming Convention

While maneuvers were named in a somewhat ad hoc manner during the first two capture orbits, the maneuver naming convention and apsis event-relative timing were normalized following the execution of OTM02. Rather than numbering the n potential RCS maneuvers sequentially, e.g., OTM01...OTMn, it was determined that, given the myriad of backup and statistical maneuver opportunities, it was more straightforward to reference maneuvers using their three-letter identifier –

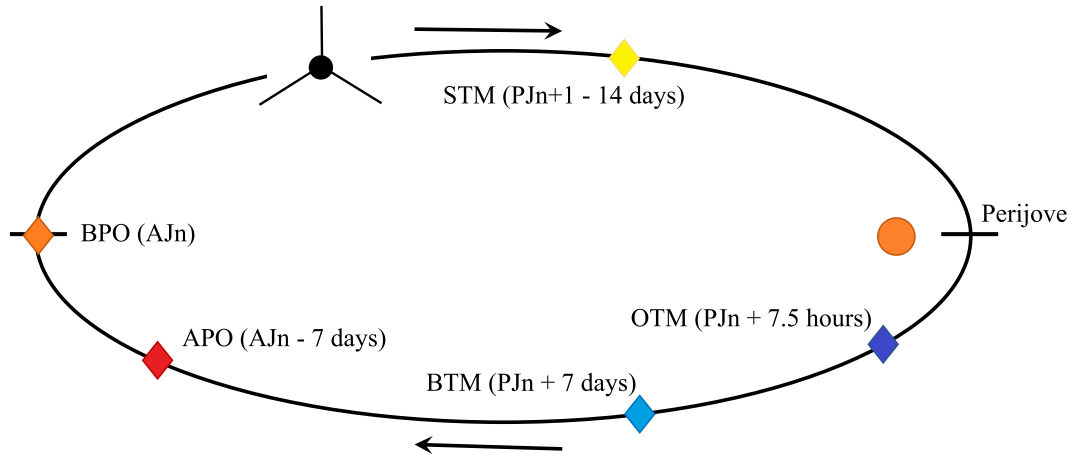


Figure 9. Juno Maneuver Opportunities, Orbit-Normal into Page, *Figure Not to Scale*

OTM, BTM, APO, BPO, or STM – and the orbit number. The maneuver names and event-relative times are compared for the first two capture orbits and the remainder of the mission in Table 1.

Table 1. Maneuver Naming Convention and Apsis Event-Relative Timing

Orbit Number	Maneuver Name	Relative Timing
0	JOI-CLN OTM00	PJ0 + 8 days APO - 0 days
1	OTM01	PJ01 + 18 days
2	OTM02 STM02	PJ02 + 6 days PJ03 - 5 days
n	OTMn BTMn APOn BPOn STMn	PJn + 7.5 hours PJn + 7 days APOn - 7 days APOn - 0 days PJ$n+1$ - 14 days

53-DAY SCIENCE ORBIT OPERATIONS

The maneuver operations schedule during the first two capture orbits was customized to allow the Juno team additional time to respond to any potential problems encountered following JOI, PJ01, or PJ02. However, by Juno's third Jupiter orbit, the team was more accustomed to operating the mission in 53-day science orbits, and, going forward, a regular maneuver cadence was established.

OTM03

While JOI-CLN and OTM01 were performed 8 and 18 days after their respective perijoves, OTM03 was – and future post-perijove OTMs will be – performed 7.5 hours after perijove. Implementing OTMs closer to perijove reduces the ΔV required to change the orbital period and achieve the desired longitude at the subsequent equator crossing while still allocating sufficient time for science operations near perijove.

OTM03 was designed to adjust the PJ04 equator-crossing longitude by 97.9 degrees and lower the radius by 4.2 km. The 908.2-second burn was executed on December 12, 2016 at 00:34:00 UTC and imparted a ΔV of 1.201-m/s (-0.264 m/s axial and 1.159 m/s lateral). Note that a negative axial ΔV magnitude is used to denote an axial burn in the -Z-direction. Figure 10 shows the OTM03 target corridor and delivery arc. The perijove altitude increases gradually at the beginning of the

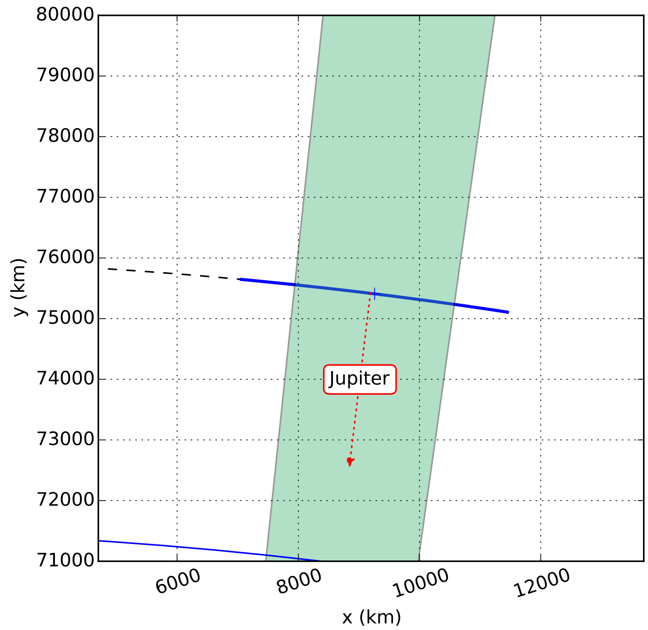


Figure 10. OTM03 Delivery Arc

53-day science orbit campaign, so an APO03 maneuver was not necessary. OTM03 execution errors were sub-sigma, so STM03 was not needed to achieve the required PJ04 delivery accuracy.

OTM04 and APO04

As of Juno's fifth orbit about Jupiter, the check valve anomaly investigation was ongoing and it was not yet known whether PRM would be implemented in the future. Consequently, the navigation team had to prepare for two possible missions – one with PRM and one without. To support a potential future PRM, an APO04 maneuver was added to lower the radii of the upcoming perijove passes.

First, OTM04 was implemented on February 2, 2017 at 20:28:03 UTC – 7.5 hours after PJ04 – to adjust the upcoming equator-crossing longitude by 24.3 degrees and the radius by 1.1 km. The primary objective of APO04, executed on February 22, 2017 at 17:00:00 UTC, was to reduce equator-crossing radius by 1012 km, which, in turn, altered the longitude by 4.4 degrees to achieve the desired targets for the PJ05 equator-crossing on March 27, 2017. The target corridor and corresponding APO04 1-σ delivery arc are presented in Figure 11. OTM04 and APO04 had a designed ΔV magnitude of 0.297 m/s (-0.080 m/s axial and 0.282 m/s lateral) and 3.766 m/s (0.616 m/s axial and 3.744 m/s lateral), respectively. Both maneuvers executed with little error so an STM was, again, not required for this orbit.

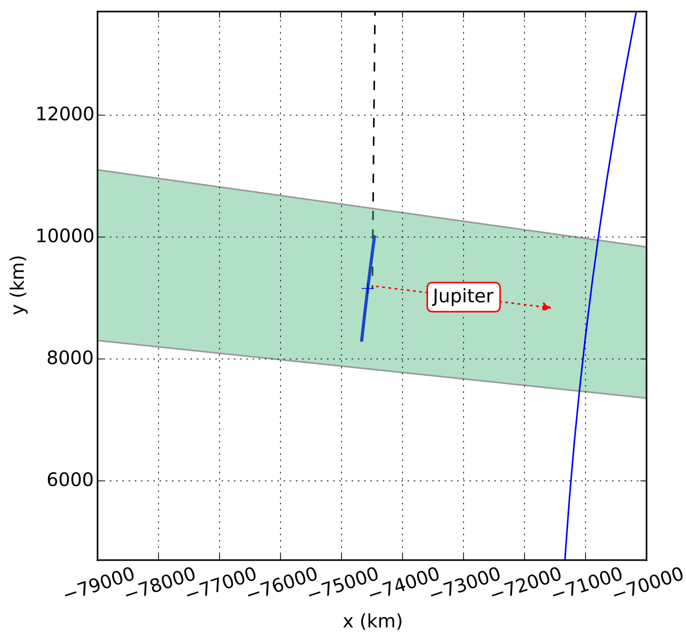


Figure 11. OTM04 and APO04 Delivery Arc

OTM05

The decision to cancel PRM was announced in mid-February 2017 and the Juno navigation team proceeded, accordingly, with the 53-day maneuver operations strategy. An APO05 maneuver was not required to mitigate the modest increase in perijove altitude that would accumulate during the sixth orbit, so only a single deterministic maneuver, OTM05, was needed. OTM05 occurred on March 27, 2017 at 16:22:14 UTC, and was a 1.828-m/s maneuver (-0.382 m/s axial and 1.769 m/s lateral) that, like previous maneuvers, executed with sufficiently little error to allow the cancelation of the subsequent STM. The OTM05 delivery arc and PJ06 equator-crossing target corridor are depicted in Figure 12.

Note that, like previous RCS burns in the orbital phase, the OTM05 vector-mode maneuver is dominated by its lateral component. This phenomenon occurs because RCS burns are performed at an Earth-pointed attitude and, early in the Juno mission, the orbital plane is nearly orthogonal to the Sun-Jupiter line. Both longitude and radius adjustments are handled primarily with in-plane burns, that, early in the mission, are aligned closely with the lateral thrusters. As the mission progresses and Jupiter continues on its heliocentric path, Juno's orbital plane will be become more closely-aligned with the Sun-Jupiter line and, thus, the axial component of vector-mode OTM and APO RCS burns will become larger than their lateral counterparts.

OTM06 and APO06

The successful PJ06 science pass was followed closely by OTM06, a 2.835-m/s (0.733 m/s axial and 2.773 m/s lateral) maneuver that began at 13:30:43 UTC on May 19, 2017. OTM06 changed the PJ07 equator-crossing longitude by 128.7 degrees and lowered the radius by 31.1 km. APO06 executed on June 8, 2017 at 18:00:00 UTC and completed the remainder of the required trajectory correction, lowering the PJ07 equator-crossing radius by 291 km and adjusting the longitude by an

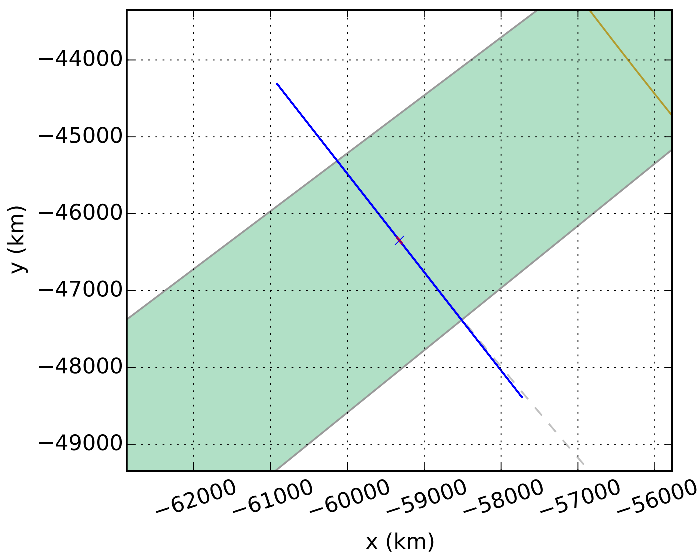


Figure 12. OTM05 Delivery Arc

additional 1.5 degrees.

The Juno spacecraft has a minimum ΔV requirement that defines the smallest axial and lateral vector-mode components – 12 mm/s and 45 mm/s, respectively – that can be performed without violating maneuver execution accuracy requirements. APO06 was designed to be 1.095-m/s maneuver with a 1.095-m/s lateral component and a 0.008-m/s axial component. Since the axial component of the maneuver was too small to execute, only the lateral portion of the burn was commanded onboard the spacecraft. Pre-burn analysis indicated that the axial portion of APO06 could be safely neglected, given that its removal introduced radial and longitudinal errors of only 0.262 km and 0.015 degrees, respectively, at the PJ07 equator crossing. The delivery arcs for OTM06 and APO06 appear in blue and red, respectively in Figure 13. Just like all the previous orbits, the STM manevuer after APO06 implementation was not needed and therefore canceled.

OTM07

OTM07 executed on July 11, 2017 at 09:24:51 UTC and is the final maneuver discussed in this paper. The burn imparted a ΔV of 2.836 m/s and possessed a vector-mode decomposition (0.741 m/s axial and 2.773 m/s lateral) that was very similar to OTM06. OTM07 altered the PJ08 equator-crossing radius by only 57.13 km, but changed the longitude by 231.34 degrees. Figure 14 shows the delivery arc for OTM07 as the blue arc. The red arc is the theoretical delivery arc for APO07 because, at the time of this writing, the APO07 maneuver has not yet executed, but is scheduled to occur on August 2, 2017 at 17:00:00 UTC. APO07 is responsible for satisfying the PJ08 equator-crossing targets of 75431.75 km radius and 322 degrees west longitude depicted in Figure 14.

SUMMARY

Through the combined efforts of the entire Juno team, the Juno spacecraft is successfully orbiting Jupiter and gathering outstanding science data since July 2016. Juno's first 12 months in orbit have been an exciting time marked with unexpected changes, but the mission's continued achievements

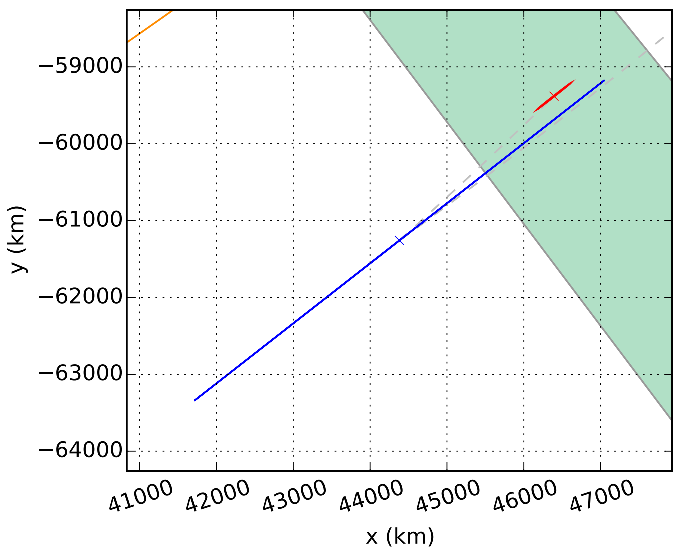


Figure 13. OTM06 and APO06 Delivery Arcs

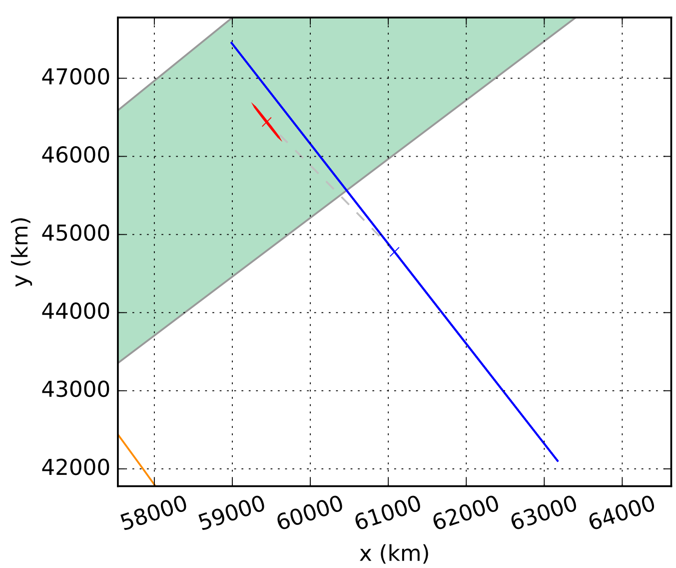


Figure 14. OTM07 and APO07 Delivery Arcs

are a testament to the hard work and dedication of the members of the Juno team. The navigation team, just one of the many teams contributing to Juno's successful operation, effectively navigated Juno through interplanetary space for its rendezvous with Jupiter in July 2016. The team shepherded the spacecraft through Jupiter orbit insertion, responded expediently to PRM delay and PJ02 safe mode entry with updated reference trajectories and maneuver operations strategies.

A summary of all main-engine and RCS vector-mode maneuvers implemented since the Jupiter approach phase began in the spring of 2016 is presented in Table 2 in Appendix B. Maneuver performance has been excellent, to date, and no STM maneuvers have been required. Equator-crossing delivery performance is aggregated in Table 3 in Appendix C. The Juno spacecraft has successfully achieved its $\pm$1-degree equator-crossing longitude delivery requirement for all science perijoves. Lastly, Table 4 in Appendix D provides details for all maneuvers – implemented and canceled – that were designed during Juno's Jupiter approach phase and first year of Jupiter operations. At the time of this writing, the Juno maneuver team continues to guide the spacecraft along its reference trajectory.

APPENDIX A: B-PLANE DESCRIPTION

The B-plane (body plane) provides a useful reference frame for characterizing spacecraft trajectories that are hyperbolic with respect to a central body of interest and is used extensively by the Juno navigation team for mapping orbit determination uncertainties and maneuver targeting. A graphical definition of the B-plane appears in Figure 15.

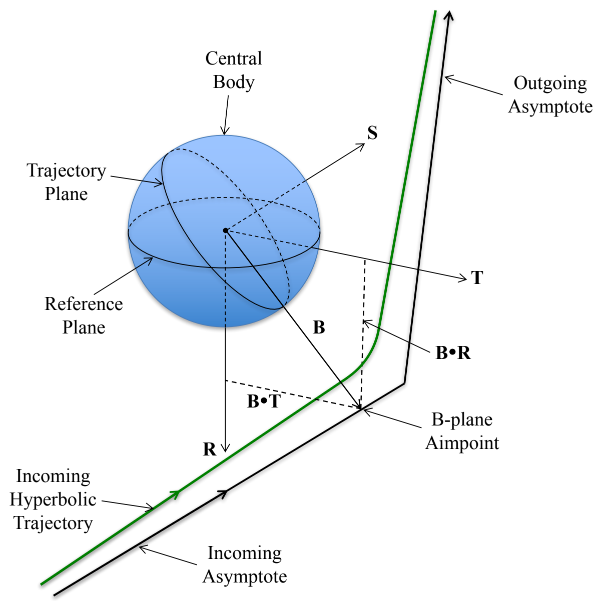


Figure 15. B-Plane Schematic[2]

The incoming trajectory (green) is hyperbolic with respect to the central body (blue). The B-plane is defined to be a plane through the center of the central body that is orthogonal to the incoming asymptote of the hyperbolic trajectory. In this definition, the vector $\boldsymbol{S}$ denotes the B-plane's surface normal direction and the vector $\boldsymbol{T}$ represents the intersection of the B-plane and a reference plane, e.g., the ecliptic, equatorial plane, etc. The orthogonal coordinate system is completed by defining $\boldsymbol{R} = \boldsymbol{S} \times \boldsymbol{T}$. The B-plane aimpoint is represented by the $\boldsymbol{B}$ vector and is often given in terms of its components, i.e., $\boldsymbol{B} \cdot \boldsymbol{R}$ and $\boldsymbol{B} \cdot \boldsymbol{T}$.

APPENDIX B: MANEUVER PERFORMANCE COMPARISON

Table 2. Estimated Maneuver Performance vs. Design

Maneuver	ΔV Magnitude (m/s)			Right Ascension (deg)			Declination (deg)		
	Est.	Design	$AP\ \sigma$	Est.	Design	$AP\ \sigma$	Est.	Design	$AP\ \sigma$
TCM11 Axial	0.282	0.279	0.002	359.659	359.660	0.239	-2.582	-2.547	0.239
TCM11 Lateral	0.139	0.139	0.015	265.424	265.677	2.3	-31.058	-29.840	2.0
JOI	542.107	541.655	0.451	268.481	268.446	0.494	62.408	62.376	0.229
JOI-CU Axial	1.160	1.155	0.003	350.349	350.381	0.180	-5.340	-5.327	0.179
JOI-CU Lateral	4.838	4.831	0.016	249.583	250.185	1.949	-50.115	-49.682	1.261
OTM01 Axial	0.054	0.051	0.003	181.752	181.652	0.811	0.408	0.397	0.811
OTM01 Lateral	0.605	0.600	0.015	267.601	267.694	1.671	-38.821	-38.465	1.308
OTM02 Axial	0.590	0.585	0.003	9.536	9.546	0.245	2.948	2.988	0.245
OTM02 Lateral	2.586	2.580	0.018	104.396	104.444	1.553	29.753	30.226	1.342
OTM03 Axial	0.266	0.264	0.003	197.340	197.412	0.331	-6.091	-6.113	0.329
OTM03 Lateral	1.152	1.159	0.016	291.082	291.087	2.418	-53.854	-53.402	1.442
OTM04 Axial	0.081	0.080	0.003	201.648	201.780	0.685	-7.671	-7.634	0.679
OTM04 Lateral	0.282	0.282	0.015	297.950	297.933	3.506	-55.660	-55.091	2.006
APO04 Axial	0.624	0.616	0.003	21.878	21.827	0.244	7.709	7.69	0.241
APO04 Lateral	3.753	3.744	0.019	103.439	103.184	2.787	-61.408	-61.815	1.316
OTM05 Axial	0.384	0.382	0.003	198.520	198.553	0.283	-6.151	-6.198	0.282
OTM05 Lateral	1.773	1.769	0.019	292.441	292.402	2.332	-54.193	-53.755	1.379
OTM06 Axial	0.744	0.733	0.003	13.140	13.144	0.231	4.025	4.061	0.231
OTM06 Lateral	2.781	2.773	0.018	112.370	112.222	2.067	50.075	49.741	1.336
APO06 Axial	0.0	0.0	NA	NA	NA	NA	NA	NA	NA
APO06 Lateral	1.099	1.095	0.016	101.931	102.488	2.511	-54.220	-54.683	1.452
OTM07 Axial	0.750	0.741	0.003	13.795	13.798	0.231	4.574	4.574	0.230
OTM07 Lateral	2.774	2.773	0.018	113.837	113.664	2.092	50.695	50.298	1.336

APPENDIX C: EQUATOR-CROSSING DELIVERY

Table 3. Equator Crossing Delivery Comparison

Equator Crossing	Epoch (ET)		West Longitude (deg)	
	Target	Achieved	Target	Achieved
PJ01	27-Aug-16 12:53:54.3	27-Aug-16 12:53:18.6	97.00	96.64
PJ02	19-Oct-16 18:13:52.0	19-Oct-16 18:13:49.4	348.85	348.82
PJ03	11-Dec-16 17:07:14.6	11-Dec-16 17:06:58.0	7.00	6.83
PJ04	02-Feb-17 13:01:43.3	02-Feb-17 13:00:49.1	277.00	276.45
PJ05	27-Mar-17 08:56:13.4	27-Mar-17 08:55:50.8	187.00	186.77
PJ06	19-May-17 06:05:06.3	19-May-17 06:05:07.9	142.00	142.02

APPENDIX C: MANEUVER DESIGN SUMMARY

Table 4 shows a summary of all of the maneuver designs presented in this paper. The rows in red indicate the canceled maneuvers.

Table 4. Maneuver Design Summary

Maneuver	Epoch (UTC)	Relative Timing		Type	ΔV (m/s)		
		Event	ΔTime		Ideal	Axial	Lateral
TCM11	3-Feb-16 17:58:51	PJ0	-152 days	RCS	0.307	0.279	0.139
JOI	5-Jul-16 02:30:00	PJ0	Centered	ME	541.65	541.65	-
JOI-CLN	13-Jul-16 17:58:51	PJ0	+8 days	RCS	4.918	1.155	4.831
OTM00	27-Jul-16 17:58:51	PJ0	+22 days	RCS	0.062	0.04	0.049
OTM01	14-Sep-16 17:58:51	PJ01	+18 days	RCS	0.604	-0.051	0.6
PRM	19-Oct-16 18:00:00	PJ02	Centered	ME	395.17	395.17	-
OTM02	25-Oct-16 17:58:52	PJ02	+6 days	RCS	2.618	0.585	2.58
OTM03	12-Dec-16 00:34:00	PJ03	+7.5 hours	RCS	1.201	-0.264	1.159
OTM04	2-Feb-17 20:28:03	PJ04	+7.5 hours	RCS	0.297	-0.08	0.282
APO04	22-Feb-17 17:00:00	PJ04	+20 days	RCS	3.766	0.616	3.744
OTM05	27-Mar-17 16:22:14	PJ05	+7.5 hours	RCS	1.828	-0.382	1.769
OTM06	19-May-17 13:30:43	PJ06	+7.5 hours	RCS	2.835	0.733	2.773
APO06	8-Jun-17 18:00:00	PJ06	+20 days	RCS	1.095	0.008	1.095
OTM07	11-Jul-17 09:24:51	PJ07	+7.5 hours	RCS	2.835	0.738	2.772

ACKNOWLEDGMENTS

The Juno Navigation Team has done a great job ”navigating” the changes that took place during the stage of the mission presented in this paper. All of the data and work presented has been the result of contributions from the whole team. The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

[1] S. Matousek, “The Juno New Frontiers Mission,” *Acta Astronautica*, Vol. 61, 2007, pp. 932–939.

[2] T. Pavlak, R. Frauenholz, J. Bordi, J. Kangas, and C. Helfrich, “Maneuver Design for the Juno Mission: Inner Cruise,” *AIAA/AAS Astrodynamics Specialist Conference*, No. AIAA 2014-4149, San Diego, California, August 4-7 2014.

[3] J. Johannesen, T. Pavlak, and J. Bordi, “Initial JOI and PRM Plans for Juno,” *AAS/AIAA Astrodynamics Specialist Conference*, No. AAS 17-633, Stevenson, Washington, August 20-24 2017.

[4] T. Pavlak, J. Johannesen, and J. Bordi, “Juno Trajectory Redesign Following PRM Cancellation,” *AAS/AIAA Astrodynamics Specialist Conference*, No. AAS 17-573, Stevenson, Washington, August 20-24 2017.

[5] P. Thompson, S. Ardalan, J. Bordi, N. Bradley, D. Farnocchia, and Y. Takahashi, “Juno Navigation for Jupiter Orbit Insertion,” *AAS/AIAA Spaceflight Mechanics Meeting*, No. AAS 17-459, San Antonio, Texas, Februdary 5-9 2017.